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Title: R&D on MgB<sub>2</sub> at LANL for Applications to Superconducting RF Cavities

Author(s): Tajima, Tsuyoshi

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# R&D on $\text{MgB}_2$ at LANL for Applications to Superconducting RF Cavities

Tsuyoshi Tajima

Mechanical Design & Engineering Group  
Accelerator Operations & Technology Division

A seminar at KEK, 17 February 2020

LA-UR-20-XXXXX

# Outline

- Introduction
- Brief history of my research on  $\text{MgB}_2$
- Recent activities and results

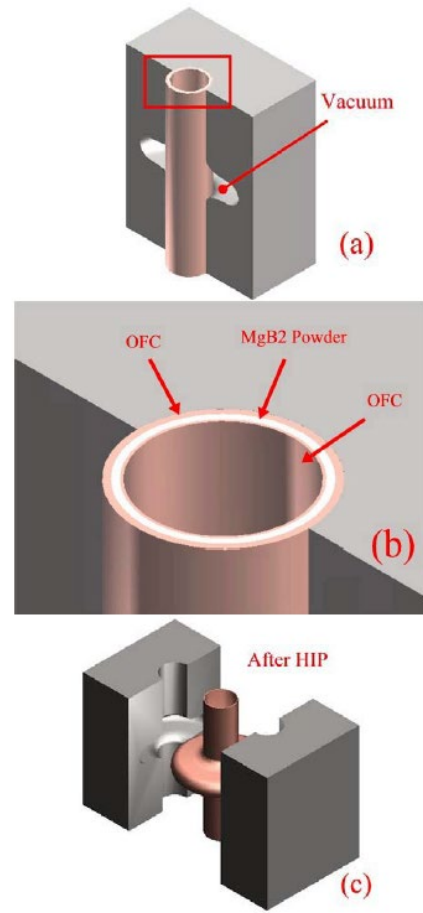
# Introduction

- Recent SRF cavities (especially 1.3 GHz elliptical cells) made of bulk Nb are approaching its theoretical limit of  $E_{\text{acc}} \sim 50 \text{ MV/m}$  ( $B_{\text{peak}} \sim 200 \text{ mT}$ ).
- While it is important to increase quality factor and production reliability and yield of high-quality Nb SRF cavities, finding a new material that could overcome the limit of Nb technology is becoming increasingly important for SRF technology to be more attractive and to open up other opportunities.
- $\text{Nb}_3\text{Sn}$  technology has become close to the application level.
- $\text{MgB}_2$  cavities of practical size have not yet been produced yet, but its high  $T_c$  of  $\sim 40 \text{ K}$  is very attractive to enable the operation at a higher temperature such as 20-25 K with cryocoolers.

# Brief history of my research on $\text{MgB}_2$

- Soon after  $\text{MgB}_2$  was discovered to be superconducting at 39 K in 2001, a feature written in a review paper caught my eyes, “absence of weak links” (at the grain boundaries). (These weak links had prevented high- $T_c$  materials from being applied for SRF cavities.)
- My first paper on  $\text{MgB}_2$  at EPAC2002 proposed to use thick  $\text{MgB}_2$  layer formed on a copper cavity using hot isostatic press (HIP).

At that time, I did not know that bulk or thick film is not so useful.



**In 2004, I wrote a paper with Collings and Sumption of OSU. The current cavity coating idea is similar to the idea written in this paper.**

INSTITUTE OF PHYSICS PUBLISHING

SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. 17 (2004) S595–S601

PII: S0953-2048(04)77346-7

# **Magnesium diboride superconducting RF resonant cavities for high energy particle acceleration**

**E W Collings<sup>1</sup>, M D Sumption<sup>1</sup> and T Tajima<sup>2</sup>**

<sup>1</sup> Laboratories for Applied Superconductivity and Magnetism, Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA

<sup>2</sup> Los Alamos Neutron Science Center, Accelerator Physics and Engineering, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

In 2005, we showed that  $R_s$  can be lower than that of Nb and there is little increase in  $R_s$  with fields up to 120 Oe limited by available power [Tajima et al. PAC2005]

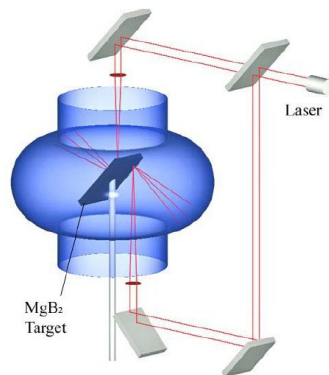


Figure 7: An idea for coating a cavity using a  $\text{MgB}_2$  target and a KrF excimer laser.

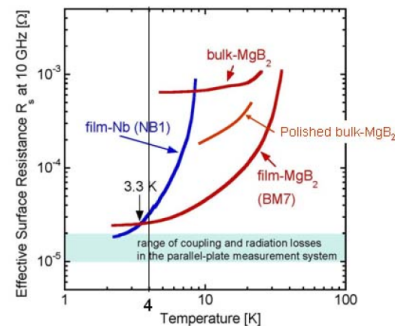


Figure 3: Surface resistance vs. temperature of a 400 nm  $\text{MgB}_2$  film coated on a sapphire substrate. Bulk samples and Nb data are shown for comparison. [6]

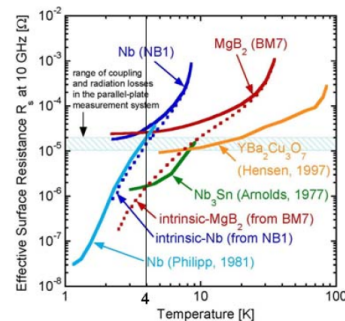


Figure 4: Prediction of intrinsic (BCS) surface resistance (dotted line) from experimental data. [6]

Deposited with reactive co-evaporation at Superconductor Technologies, Inc. (STI)



Figure 5:  $\text{MgB}_2$  coated Nb disks of 14.6 mm in diameter.

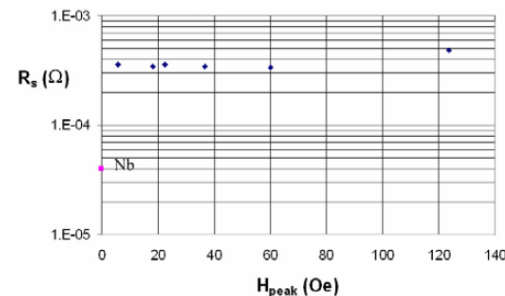


Figure 6:  $R_s$  of the Nb  $\text{TE}_{011}$  mode cavity with a  $\text{MgB}_2$  sample at the center of the bottom plate, as a function of the peak magnetic field on the sample. The data was converted to 10 GHz using an  $f^2$  law.

Collaboration with Romanenko at Cornell

In 2005-2006, we proposed to coat cavity with pulsed laser deposition (PLD), but the PLD films had poor quality [Tajima et al. EPAC2006]

$T_c \sim 27$  K

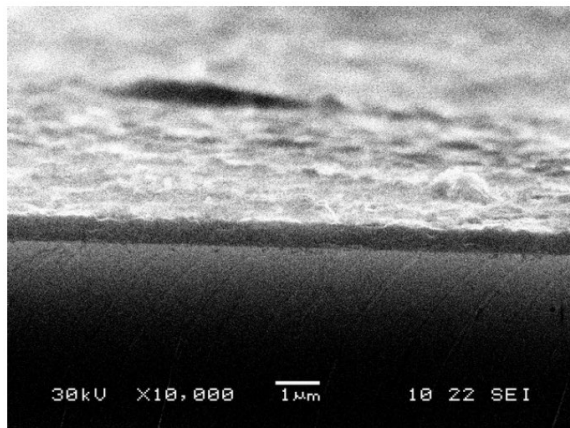


Figure 3: A SEM image of the cross section of off-axis PLD  $\text{MgB}_2$  film (ID: 300705v) on  $\text{Al}_2\text{O}_3\text{-C}$  substrate. The film thickness is 500-700nm.

Tested by Romanenko at Cornell

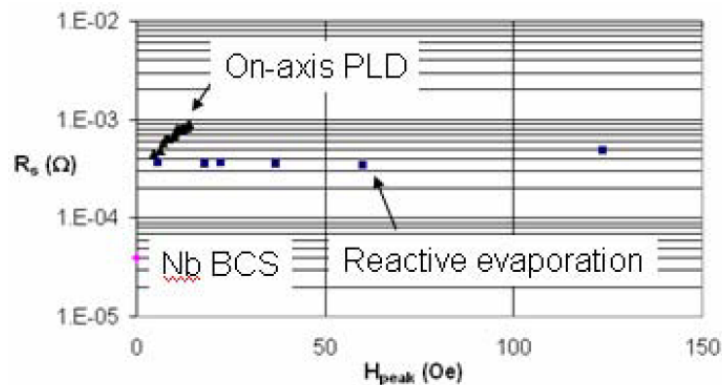


Figure 6: Surface resistance at 10 GHz as a function of surface magnetic field. The data was scaled from 6 GHz data using  $f^2$  law.

Collaboration with Yue Zhao of U. Wollongong, Australia

In 2007, we started high-power RF tests with 2-inch diameter disks in collaboration with SLAC using 11.4 GHz RF short pulse ( $\sim 1 \mu\text{s}$ ) and a  $\text{TE}_{013}$ -mode cavity

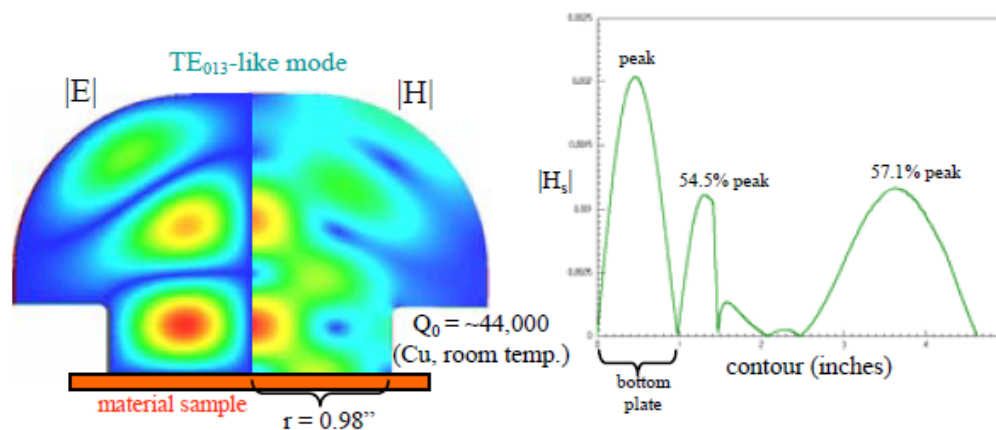


Figure 2: Electric and magnetic fields in the “mushroom” cavity (left) and magnetic field profile along the surface of the cavity (right).

[Tantawi et al. PAC2007]

**Due to the low Q of the host cavity made of copper,  $R_s$  did not have enough sensitivity. Also, thermal effect seems to have been involved despite a short pulse is used.**

STI film deposited at 550 °C on top of ALD alumina

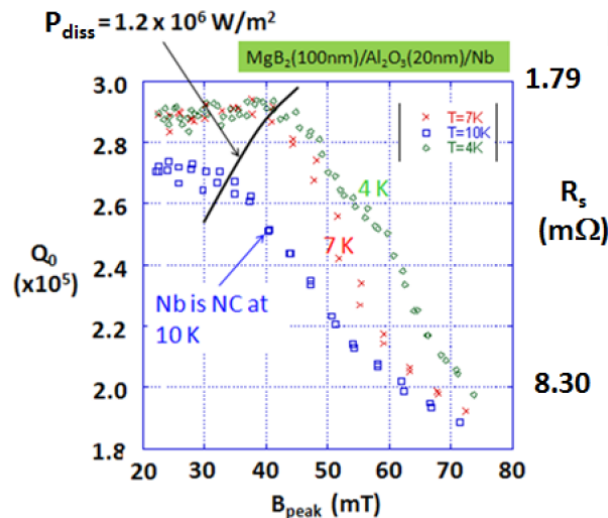


Figure 11:  $Q_0$  as a function of  $B_{\text{peak}}$  at 4 K, 7 K and 10 K for the  $\text{MgB}_2(100 \text{ nm})/\text{Al}_2\text{O}_3(20 \text{ nm})/\text{Nb}$  sample shown in Fig. 8. The solid line is a curve described by Eq. (2) with  $P_{\text{diss}} = 1.2 \times 10^6 \text{ W/m}^2$ .

[Tajima et al., SRF2011]

Inter-diffusion layer causes high RF loss

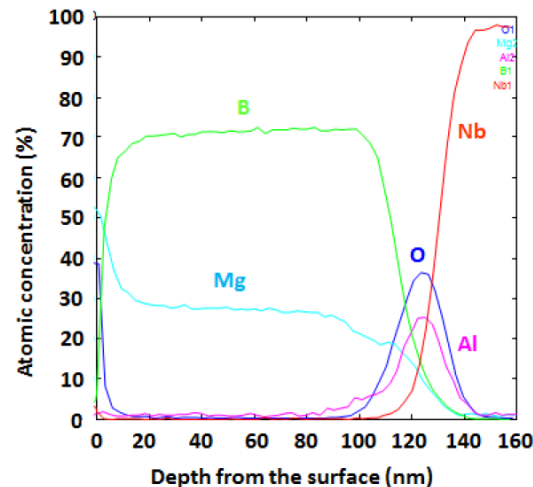


Figure 12: Auger depth profile of the  $\text{MgB}_2(100 \text{ nm})/\text{Al}_2\text{O}_3(20 \text{ nm})/\text{Nb}$  sample shown in Fig. 8. Inter-diffusion of coating components at the interfaces is observed.

# In 2010, we started using magnetization measurements to evaluate vortex penetration field $B_{vp}$ to determine the fundamental limit of $MgB_2$ thin films

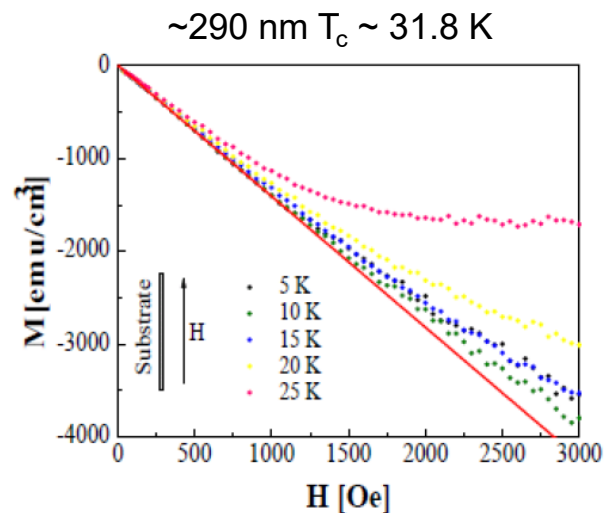


Figure 4: Magnetization curves as a function of applied magnetic field at various temperatures for ~290 nm thick  $MgB_2$  film ( $T_c \sim 31.8$  K) deposited on a Si substrate at Kagoshima Univ.

E-beam co-evaporation at  
**250 °C**  
 Base p  $\sim 1 \times 10^{-9}$   
**Torr**  
 Collaboration  
 with Doi et al. of  
 Kagoshima U.,  
 Japan

[Tajima, Haberkorn, Civale et al. LINAC2010]

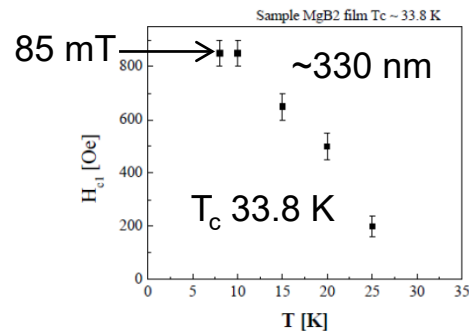


Figure 7:  $H_{c1}$  vs. sample temperature from magnetization measurements of ~330 nm thick  $MgB_2$  sample prepared by Kagoshima Univ.

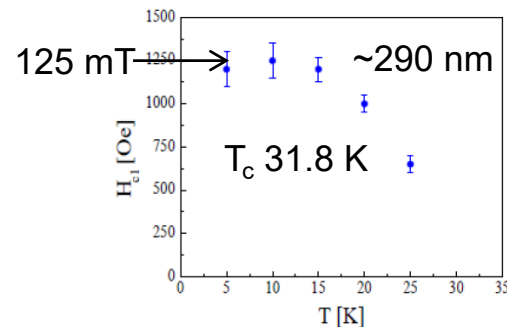
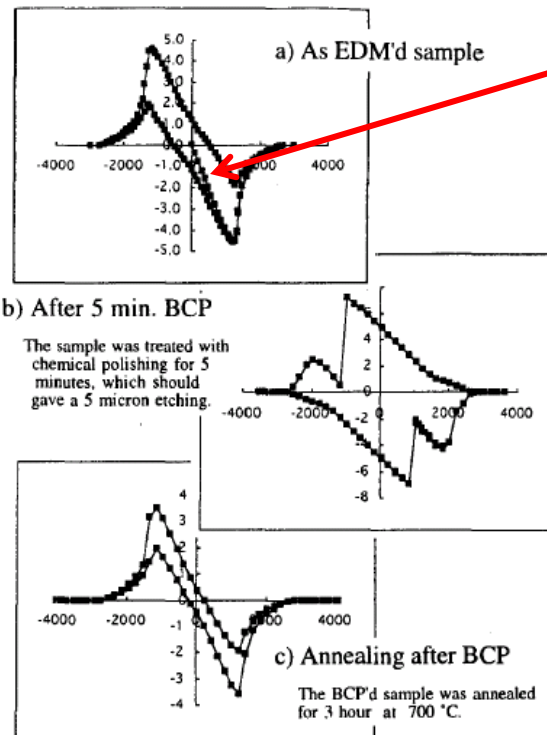


Figure 8:  $H_{c1}$  vs. sample temperature from magnetization measurements of ~290 nm thick  $MgB_2$  sample ( $T_c \sim 31.8$  K) prepared by Kagoshima Univ.



We are looking at only this part

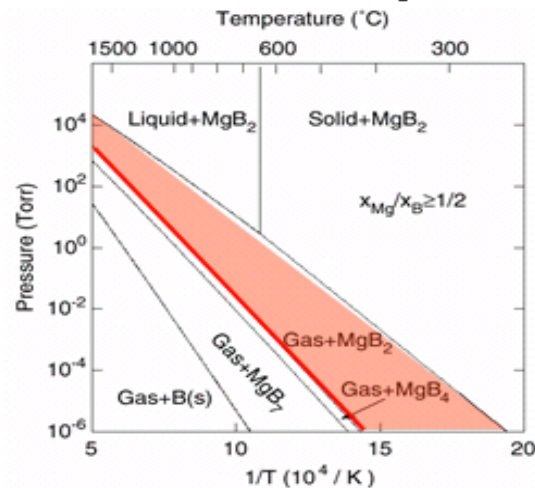
**Magnetization measurements were used for SRF cavity research in 1995 by Saito and Wake of KEK to evaluate the effect of surface treatments by looking at hysteresis curves.**

**The larger hysteresis means more imperfections and/or dislocations since vortices get pinned by them.**

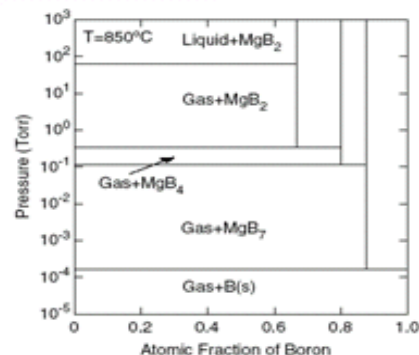
Fig. 2. Hysteresis appeared in magnetization curves. a) as EDM'd sample, b) after chemically polished the EDM'd sample, c) annealed after the CP'd sample.

[Saito, Wake, SRF1995]

# Keys to Growth of $\text{MgB}_2$ Films



Liu *et al.*, APL 78, 3678 (2001)



— **Keep a high Mg pressure for phase stability**

For example, at  $600^{\circ}\text{C}$  Mg vapor pressure of 0.9 mTorr or Mg flux of 500  $\text{\AA}/\text{s}$  is needed

— **No need for composition control**, as long as the Mg:B ratio is above 1:2.

— **Keep oxygen away**: Mg reacts strongly with **oxygen** - forms  $\text{MgO}$ , reduces Mg vapor pressure.

— **Avoid carbon**: **Carbon** doping reduces  $T_c$  and increases resistivity

[Xi, [Thin film workshop, JLAB, 18-20 July 2012](#)]

# Summary of $\text{MgB}_2$ deposition techniques that we have evaluated

Reactive Co-evaporation by Brian Moeckly et al., at STI

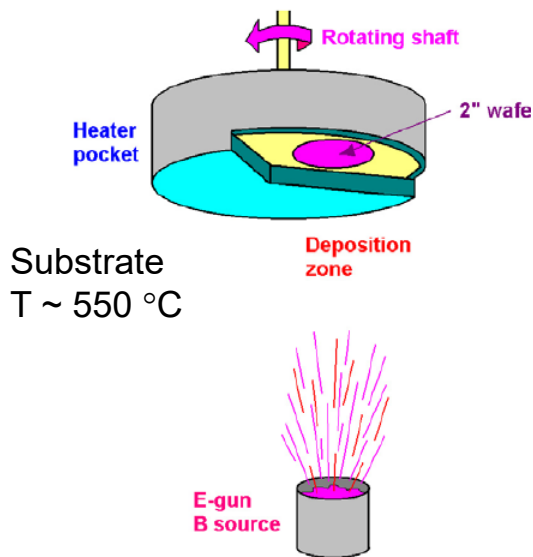


Figure 1:  $\text{MgB}_2$  coating system at STI. [5]

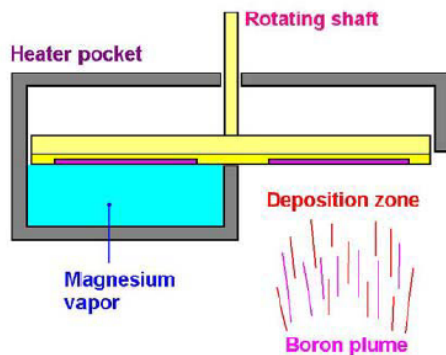
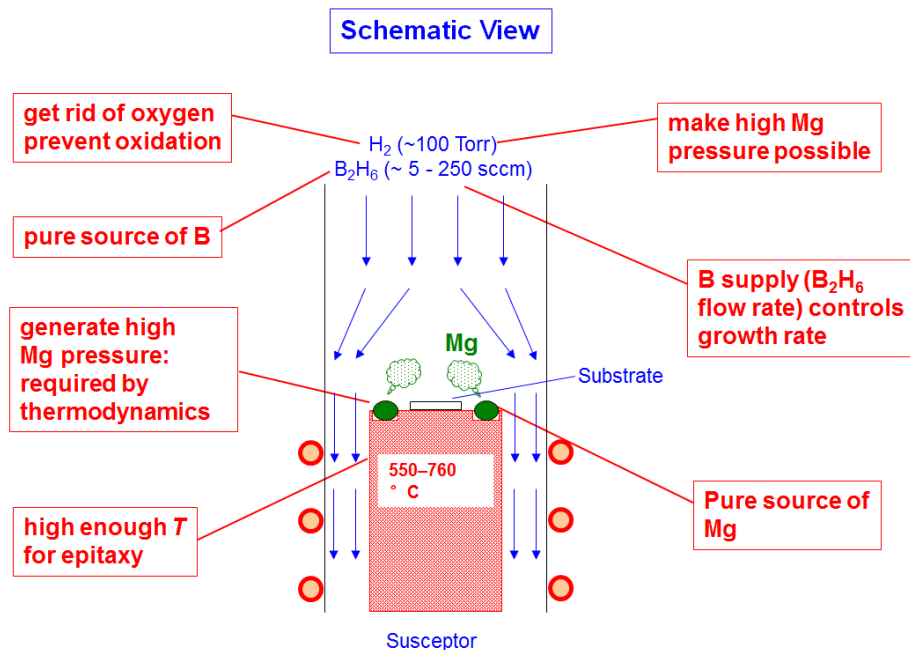


Figure 2: Cross section of the deposition chamber. [5]

[Moeckly et al., ASC2004]  
[Tajima et al., PAC2005]

# Summary of $\text{MgB}_2$ deposition techniques that we have evaluated (cont.)

## Hybrid Physical-Chemical Vapor Deposition

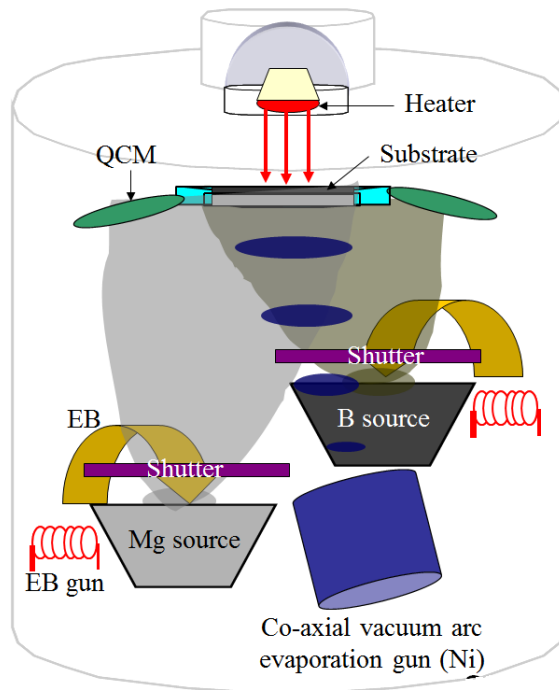


$T_c \sim 40 \text{ K}$

[Xi, [Thin film workshop, JLAB, 18-20 July 2012](#)]

# Summary of $\text{MgB}_2$ deposition techniques that we have evaluated (cont.)

E-beam co-evaporation by Toshiya Doi et al. of Kagoshima U., Japan



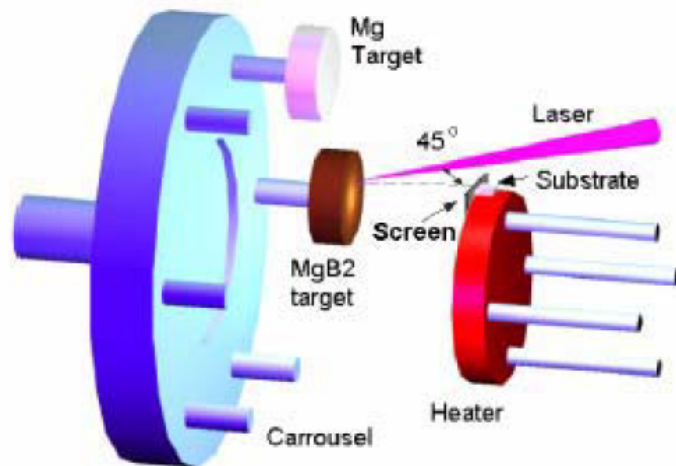
Requires base pressure  $< \sim 1 \times 10^{-9}$  Torr to avoid the effect of oxygen

$T_c \sim 32$  K  
Substrate  $T \sim 250$  °C

[Nagatomo et al., Physica C 426 (2005) 1459]

# Summary of $\text{MgB}_2$ deposition techniques that we have evaluated (cont.)

Off-axis Pulsed Laser Deposition (PLD) by Y. Zhao of U. Wollongong, Australia



$T_c \sim 27 \text{ K}$

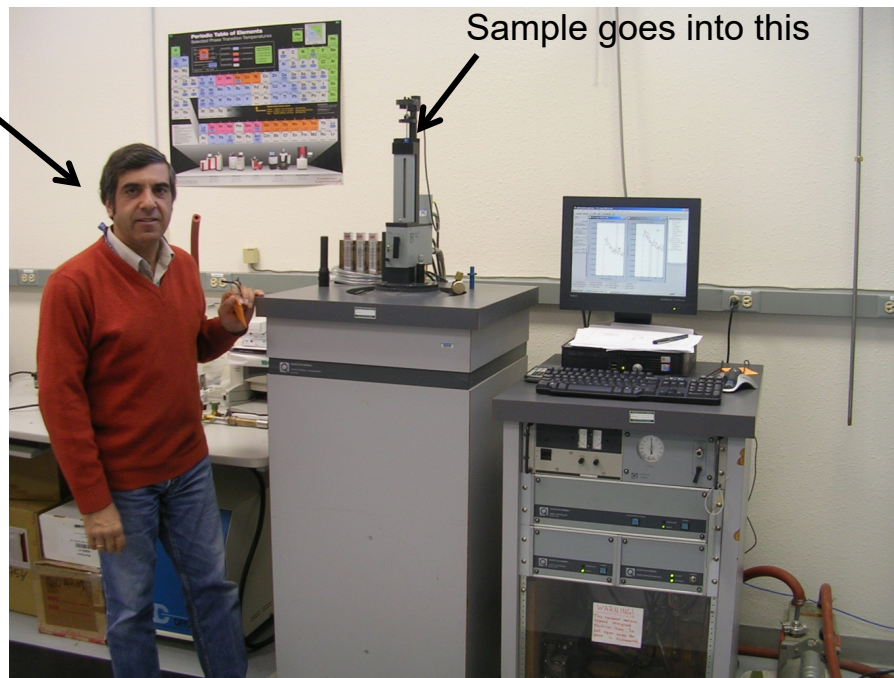
Substrate  
 $T \sim 680 \text{ }^\circ\text{C}$

Figure 1: An illustration of off-axis PLD [1].

A KrF laser ( $\lambda=248 \text{ nm}$ ,  $25 \text{ ns}$ ) was used in 120 mTorr Ar atmosphere, then an *in-situ* annealing was carried out at  $680 \text{ }^\circ\text{C}$  for 2 min in a 760 Torr Ar atmosphere [7].

# Magnetic vortex penetration field ( $B_{vp}$ ) measurements using a Quantum Design SQUID magnetometer seem to be a reliable method to determine a fundamental limit

At LANL, Leonardo Civale and his postdocs have been carrying out these measurements

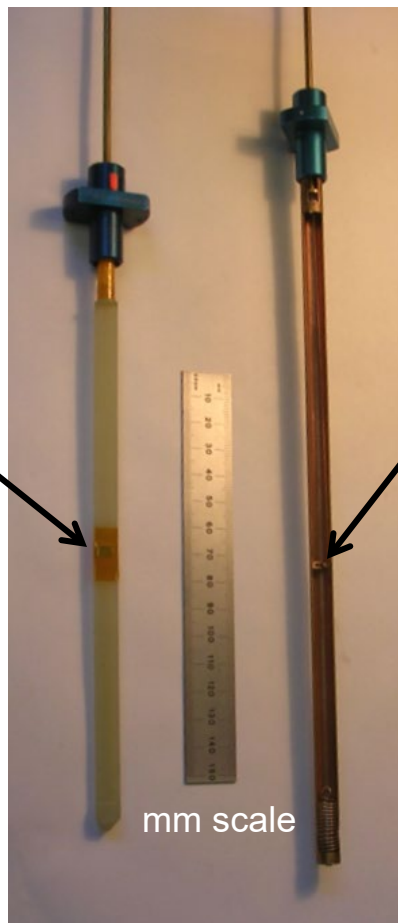


# Samples

Typically 6 mm x 6 mm for coated films

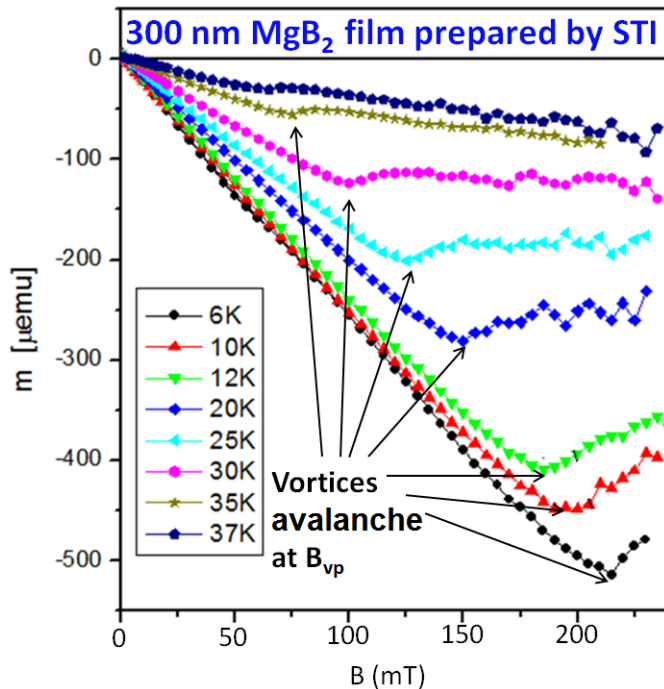
Nb reference was a rod with 2 mm diameter and 10 mm long cut out from a single grain RRR>300 Nb sheet

Rod or ellipsoid is better due to less edge effect, but difficult to uniformly coat



This sample holder has an angle adjustment mechanism

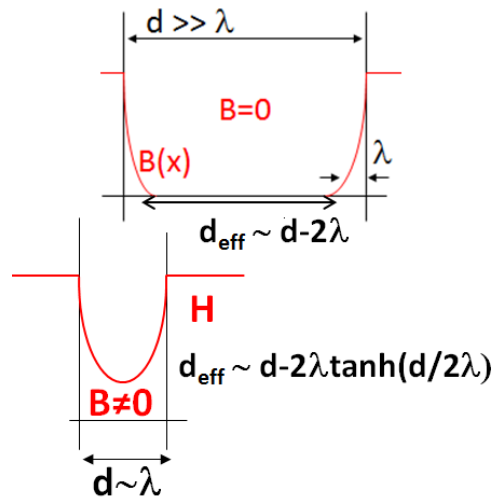
Meissner slope is proportional to the volume of the film, making it difficult to measure ultra-thin films due to small signal. Our present limit is  $\sim 200$  nm



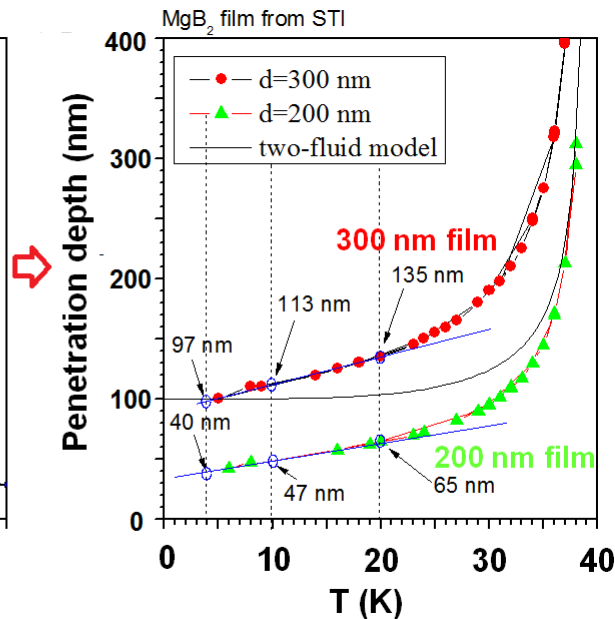
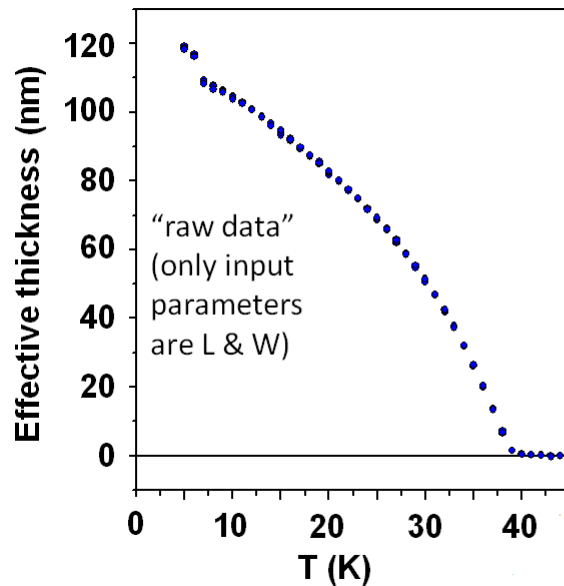
Meissner state:

$$dm/dH = -V_{\text{eff}}/4\pi \propto d_{\text{eff}}$$

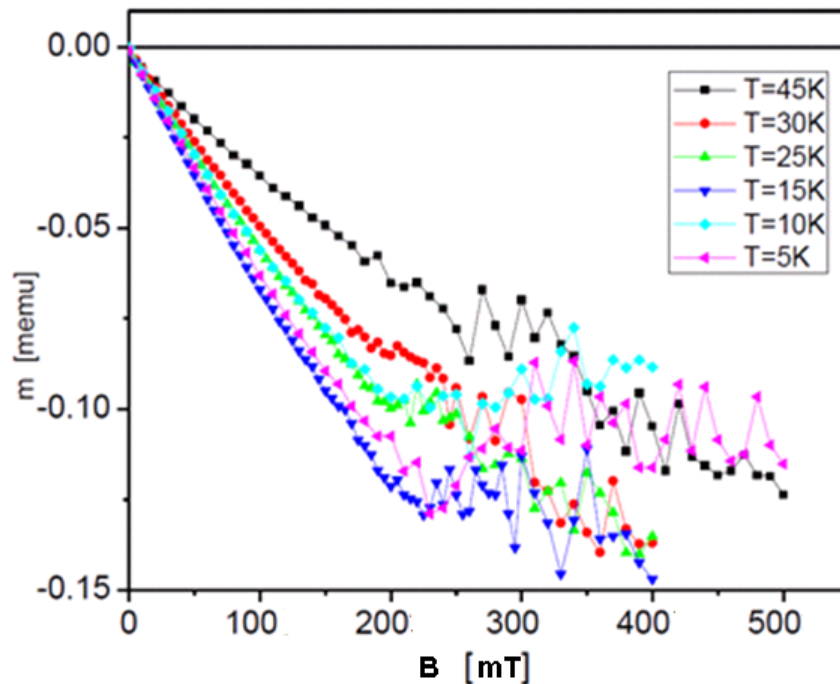
Slope changes with  $T$  due to the change in  $\lambda$



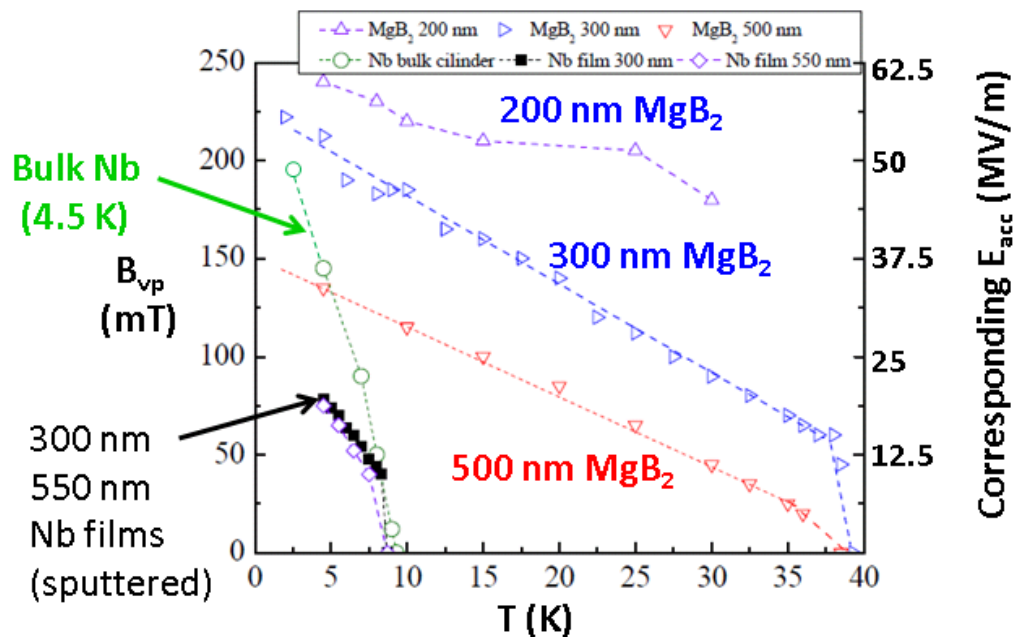
**Penetration depth can be estimated from effective thickness.**  
**Penetration depth increases with higher temperature.**  
**This causes the reduction of effective thickness.**



**With a 200 nm sample, the signal got quite noisy at high fields, but was still measurable.**



Summary of  $B_{vp}$  for STI films (200, 300 and 500 nm) compared with cavity-grade bulk Nb and sputtered Nb film.  **$MgB_2$  thin films show remarkably high  $B_{vp}$  !!**

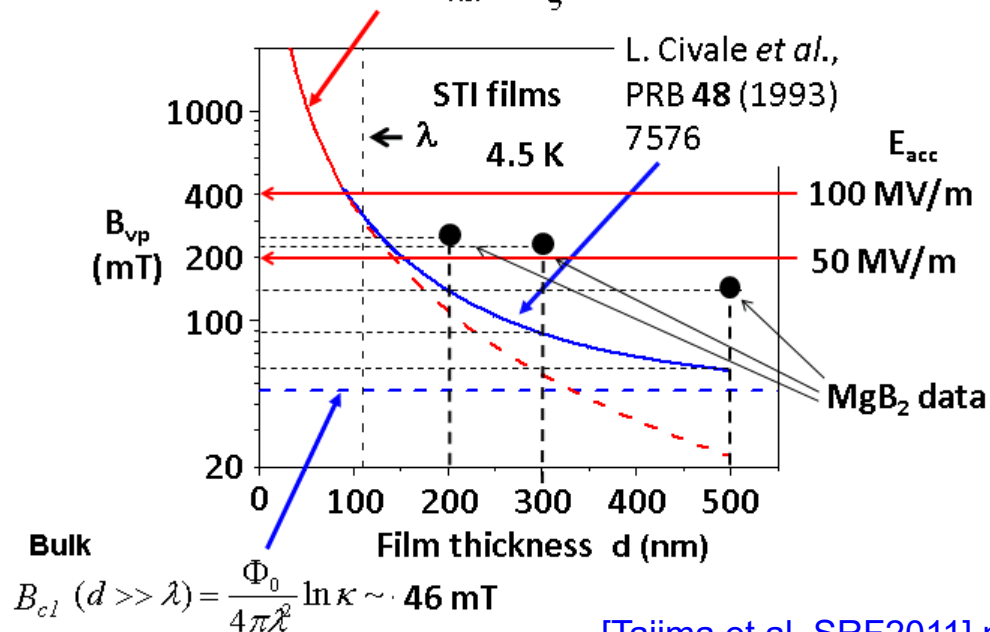


[Tajima et al. SRF2011] modified

Assume  $B_{peak}/E_{acc} = 4 \text{ mT}/(\text{MV/m})$

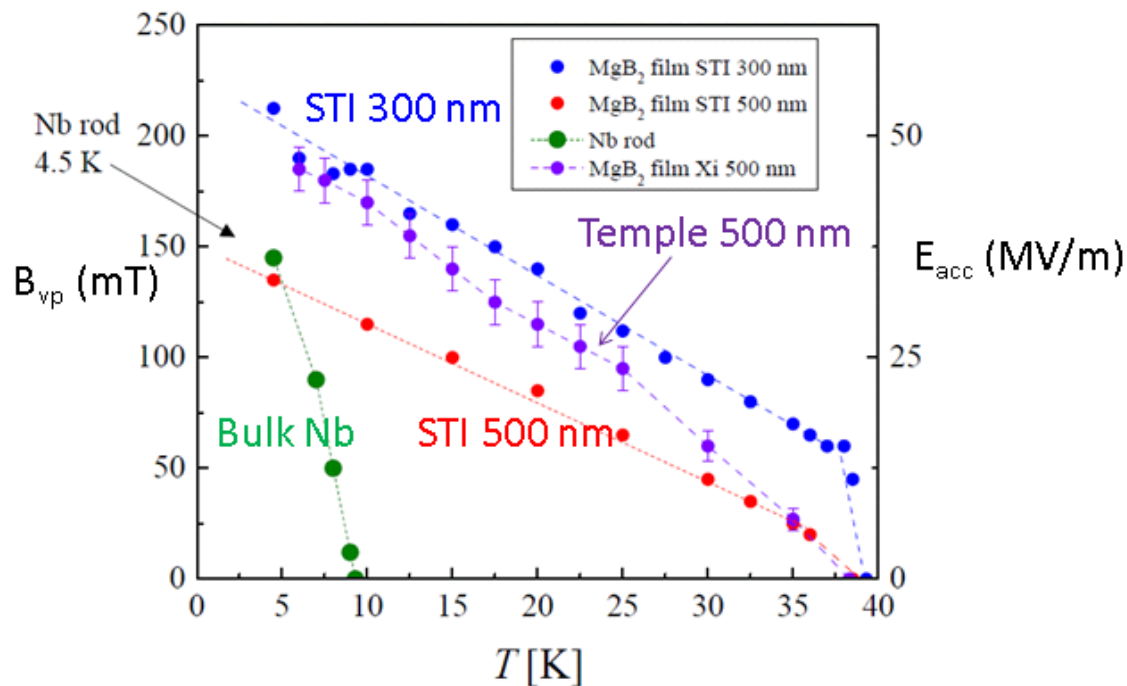
Comparison with theoretical curve of  $B_{c1}$  for thin films assuming  $\lambda = 110$  nm and  $\xi = 6$  nm. **Important finding here was that even the films with  $d > \lambda$  have high  $B_{vp}$**

$$B_{c1} (d \ll \lambda) \approx \frac{2\Phi_0}{\pi d^2} \ln \frac{d}{\xi} \quad \text{Gurevich, APL 88 (2006) 012511}$$

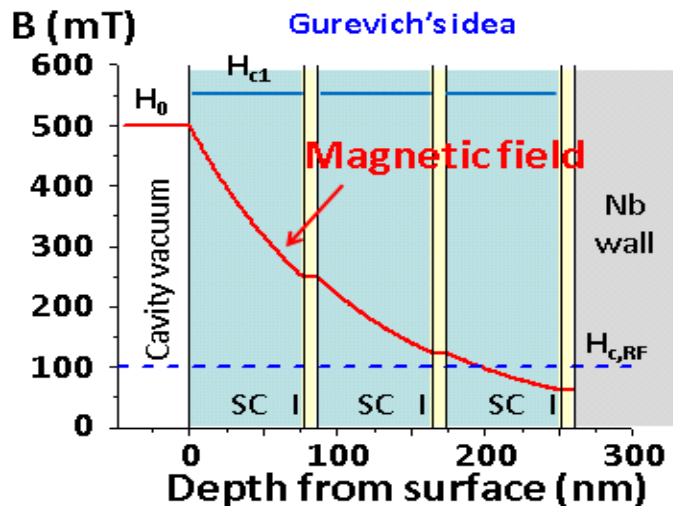


[Tajima et al. SRF2011] modified

Temple University (Xiaoxing Xi's group) samples prepared with hybrid physical chemical vapor deposition (HPCVD) also showed high  $B_{vp}$

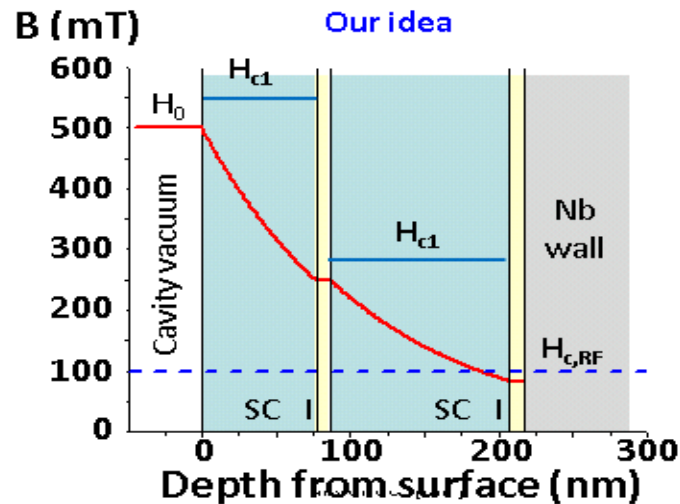


There is a possibility that we can achieve  $\sim 500$  mT ( $E_{\text{acc}} \sim 125$  MV/m) even with 2 layers of  $\text{MgB}_2$



**Fixed thickness multilayers:**

- $d \leq 77\text{nm}$  for  $H_{c1} \geq 5500$  Oe
- 3 layers needed
- coating curved walls with very thin uniform of layers is challenging

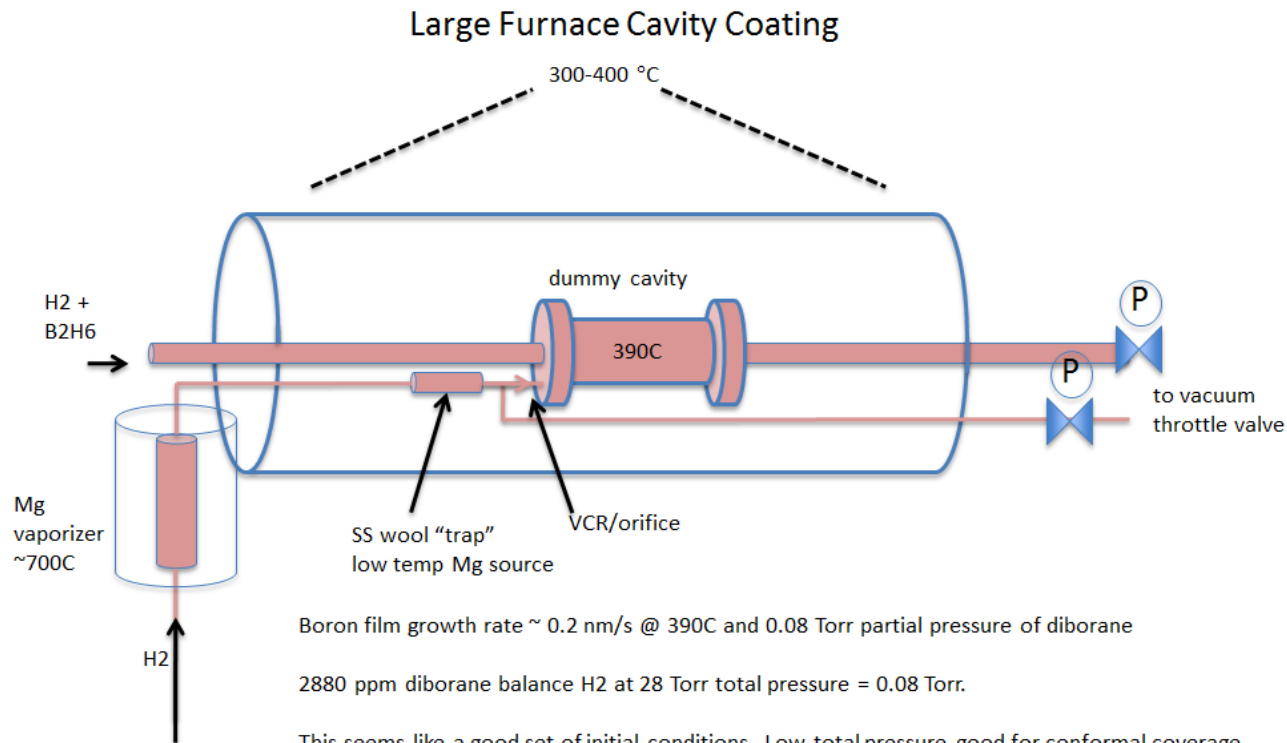


**Variable thickness multilayers:**

- $d_1 \leq 77\text{nm}$  for  $H_{c1} \geq 5500$  Oe
- only 2 layers needed
- 2<sup>nd</sup> layer is thicker:  $100\text{nm} \leq d_2 \leq 120\text{nm}$

[Tajima et al., SRF2011]

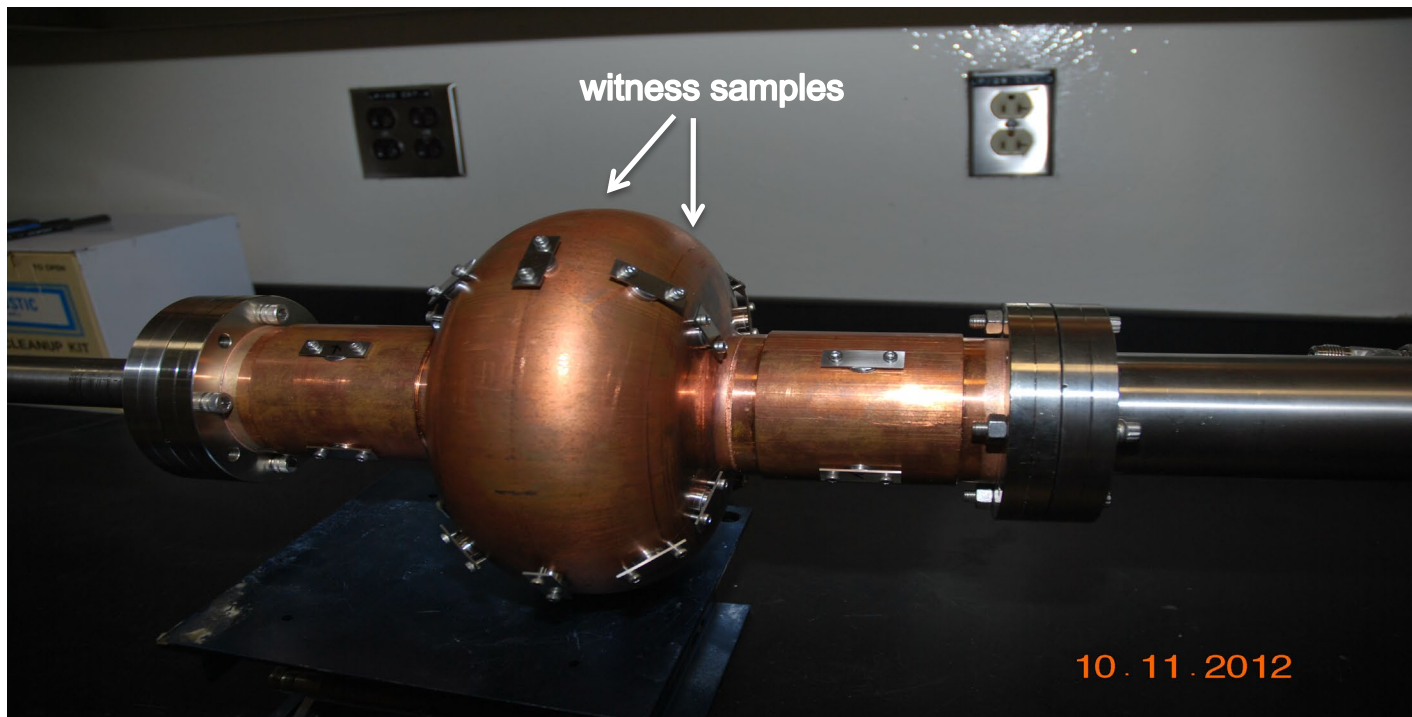
# We tried to coat a uniform B layer using diborane ( $B_2H_6$ ), then react it with Mg vapor to form a uniform $MgB_2$ layer



# MgB<sub>2</sub> CVD reactor for a 1.3 GHz cavity at TA-35-213



**A 1.3 GHz copper cavity with 28 holes for samples. Many samples were 6 mm x 6 mm x 0.43 mm sapphire**



10.11.2012

## **The experiments moved to TA-53-0017 (SRF Lab at LANSCE) in 2015 for the following reasons.**

- We can accelerate the tests since it is at a non-secure location, i.e., uncleared US citizens and foreign nationals can work without being escorted.
- Close to the infrastructure for SRF cavity preparation and testing (HPR, clean room, cavity testing environment, etc.).
- The TA-35-213 infrastructure was dismantled and the area was changed for other activities.

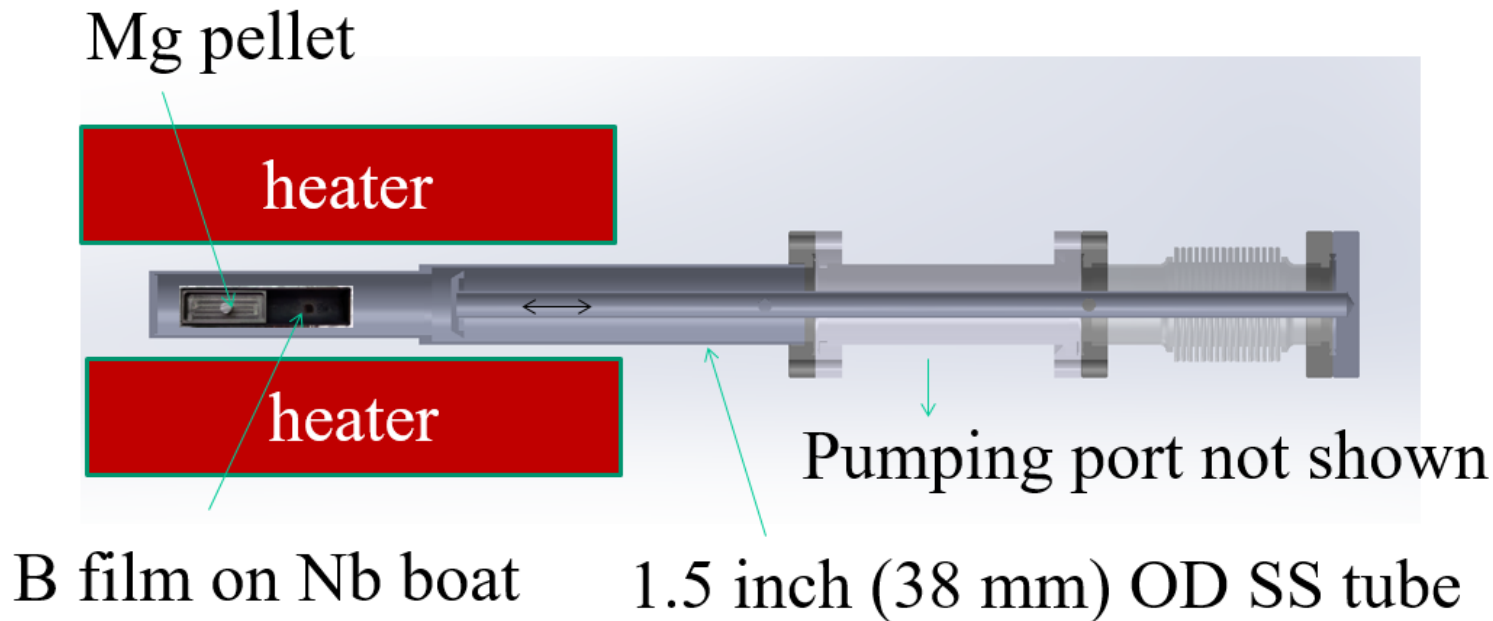
# Results of the tests at TA-53-0017 (SRF Lab) in 2015 (the final year of previous project)

- We focused on the reaction of B with Mg since we did not have to use toxic  $B_2H_6$  gas and we already had many Boron films from the work at TA-35-213.
- We found the conditions to get superconducting  $MgB_2$  films.
  - Confine B film with a Mg pellet and Ar gas and heat it up.
  - The details are in [Tajima et al., SRF2015, p. 700]

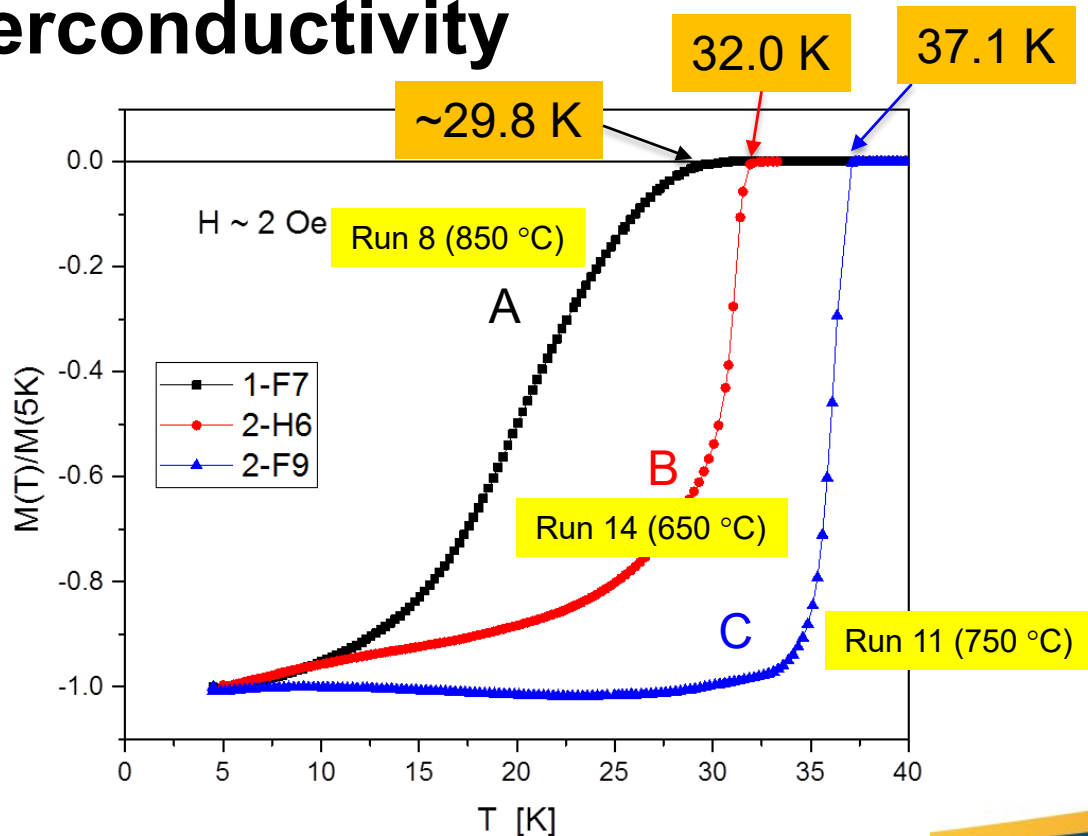
# Procedure to get $\text{MgB}_2$ at the tests in 2015

- Bake the system at  $\sim 150^\circ\text{C}$  under vacuum for  $\sim 20$  min
- Fill the system with UHP Ar gas up to 1/3 psi
- Plug the hot zone with a Mg pellet and a B film
- Raise the temperature to a planned value
- Hold it for 50 min
- Quench it to  $\sim 40^\circ\text{C}$  in  $\sim 13$  min

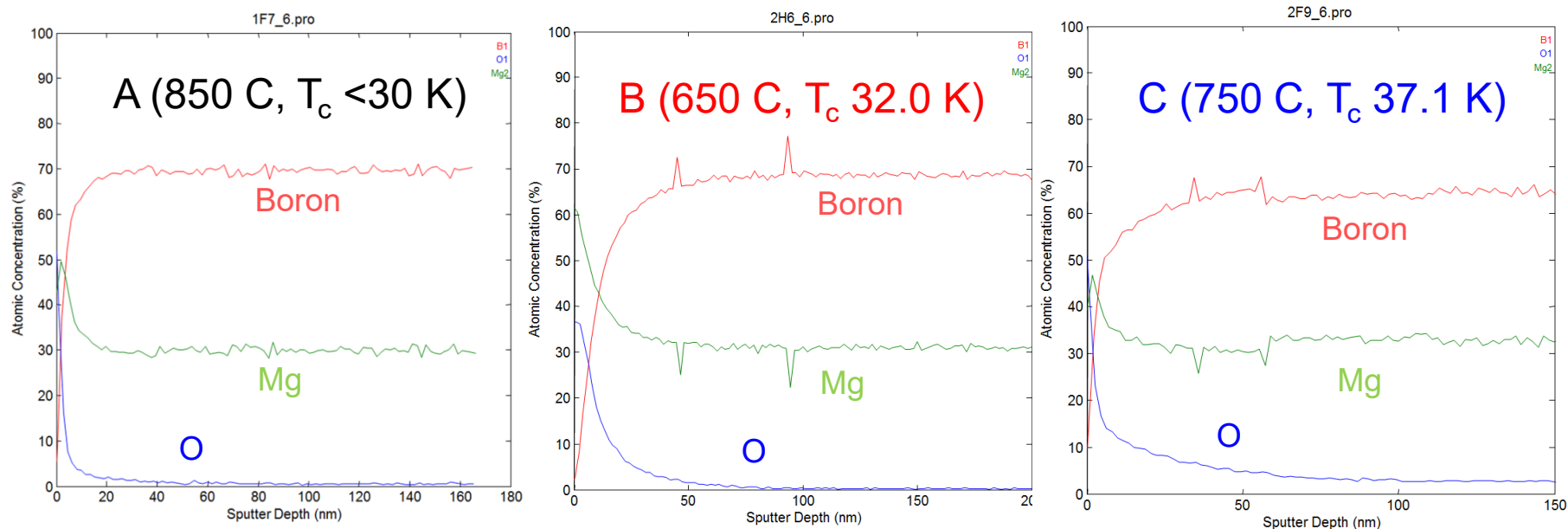
# Experimental test set up in 2015. The same set up was used for recent tests as well.



# Magnetization measurement results to check the superconductivity



**Auger Electron Spectroscopy (AES) depth profile showed the one at 750 C has the closest stoichiometric ratio of Mg:B = 1:2**



# From 2018, we restarted $\text{MgB}_2$ work as a part of US-Japan Cooperation Project

- LANL
  - Design and build a new coating system to coat 1.3 GHz 1-cell cavities
  - Provide them to KEK for testing with new diagnostics system to be developed.
- KEK
  - Develop a fixed (and rotating arm) T-map system.
  - Develop a magnetic field mapping system.
  - Test the  $\text{MgB}_2$  cavities provided by LANL.
- Due to insufficient funding, building the new coating system has been delayed.
- We restarted the parameter optimization work using a small existing system.
- The following slides were presented by Sakai-san at the TTC meeting held at CERN on 05 Feb. 2020. They summarize the recent  $\text{MgB}_2$  work at LANL.



# MgB<sub>2</sub> work at LANL in collaboration with KEK

LANL: Tsuyoshi Tajima, Paolo Pizzol, Anju Poudel, Leonardo Civale, Ivan Nekrashevich, Roland Schulze

KEK: Hiroshi Sakai, Takafumi Okada, Eiji Kako, Kensei Umemori, Taro Konomi

*TTC Meeting, CERN, 04-07 February 2020*



# Outline

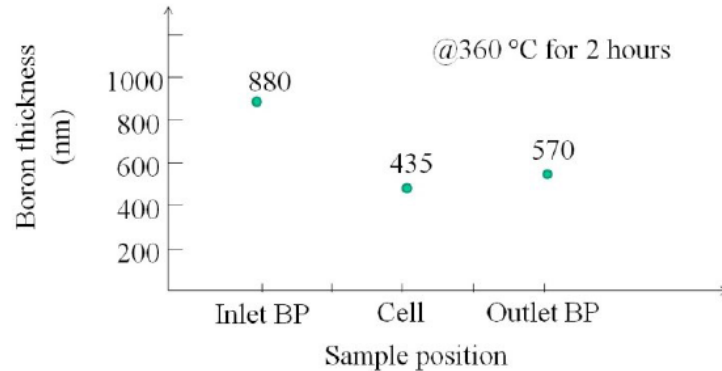
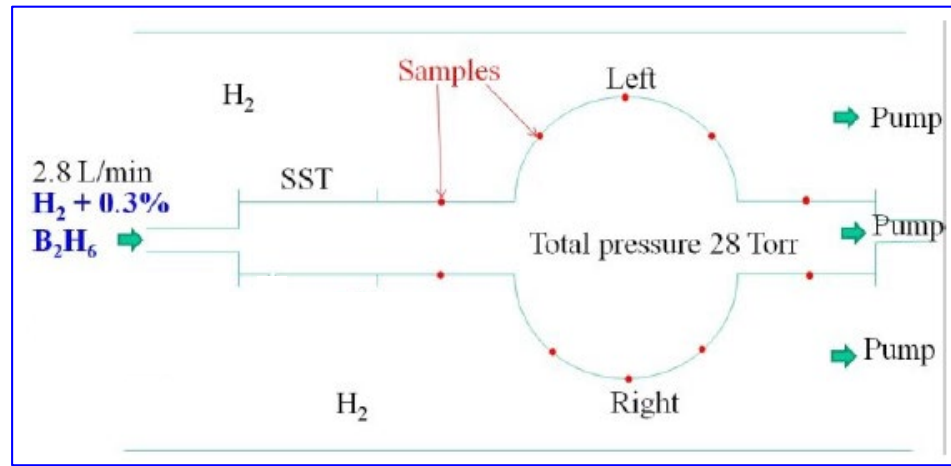
- A short description of the coating technique developed at LANL.
- Recent test results
- Design of the coating system to coat 1.3 GHz elliptical cavities.

# LANL coating technique

- LANL had a project on  $\text{MgB}_2$  from 2010 - 2015. We developed a technique to coat boron (B) first, then react it with Mg vapor (2-stage process). [e.g. Tajima et al., SRF2015, p. 700]
- We restarted the  $\text{MgB}_2$  work as a US-Japan Cooperation Project in 2018.
  - Since we lost the large furnace and equipment at TA-35 that were used in the previous project, they started to design a new coating facility at TA-53 (Tsuyoshi's lab) based on their previous experience at TA-35.
  - In November, 2019, we restarted experiments to optimize parameters for B and Mg reaction using a small system at TA-53 and the B samples obtained in the previous project.

# LANL coating technique (1<sup>st</sup> stage: coating of B layer)

- Flow  $B_2H_6$  gas inside the cavity while keeping the cavity surface at a temperature 250 – 400 °C.
- The  $B_2H_6$  decomposes and a B layer is formed on the cavity surface.
- By controlling the temperature, deposition rate can be controlled, i.e., the higher the temperature, the higher the deposition rate. Thereby the thickness profile can be controlled.
- Usually, cell is thinner than beam pipes.



If the Inlet BP temperature is lower, e.g., 250 °C, the thickness can be reduced.

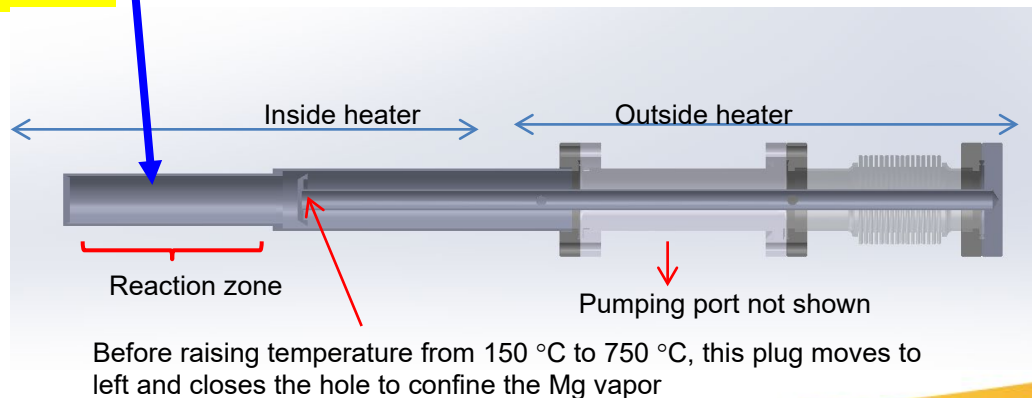
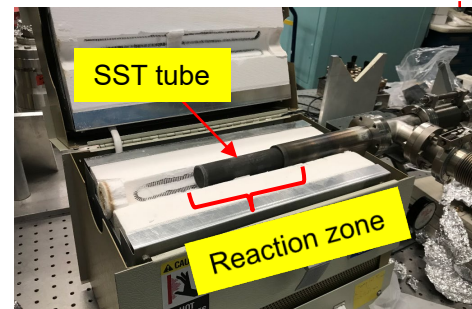
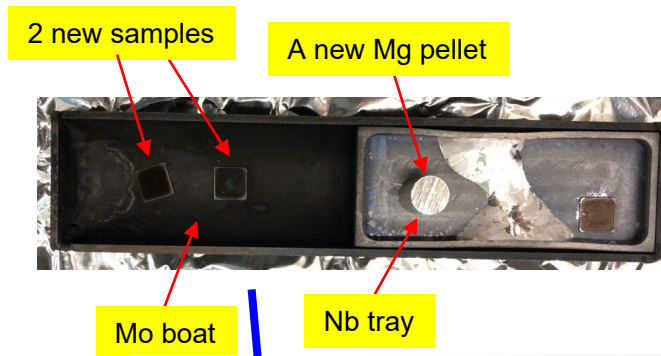
# LANL coating technique (2<sup>nd</sup> stage: reaction of B layer with Mg vapor)

- Prebake the system up to 200 °C under vacuum.
- Cool down to room temperature, add Mg pellets, bake out the system at 150 °C for >1 h under vacuum.
- Fill the chamber with UHP Ar gas up to 1/3 psi
- Plug the reaction zone to confine Mg vapor
- Heat it up to a planned temperature such as 750 °C and hold it at the temperature for planned period of time.
- Cool down the system fast enough to prevent formed  $\text{MgB}_2$  from decomposing.

# The B films obtained from the previous project

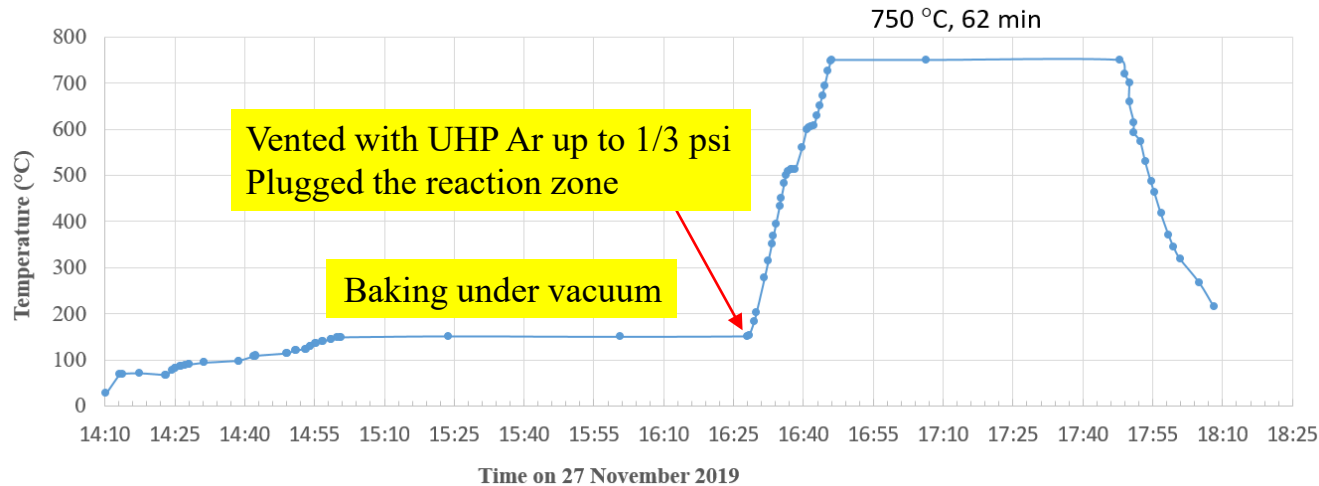
- The previous project used a 1.3 GHz elliptical 1-cell cavity with coupons attached on inlet and outlet beam pipes and cell equator.
- 22 coating runs at TA-35 were performed during the previous project and most of unused samples have been kept in a vacuum desiccator. Most samples have pure B or B with <15 % Mg, 100 – 1000 nm thick.
- They are stored in 3 carriers with each carrier having 81 samples of 6 mm x 6 mm with either sapphire or Nb substrate.
- The sample designation is carrier # - column row # such as 2-B4.

# We restarted the test that ended on 28 June 2015 (run 15)



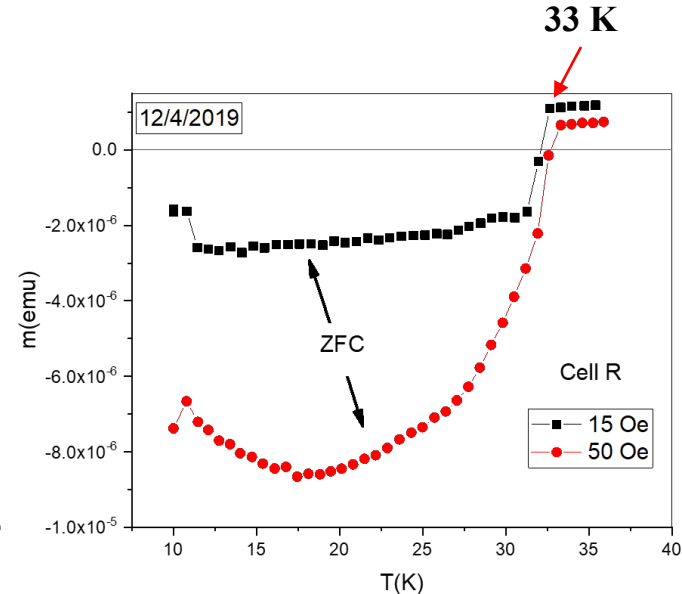
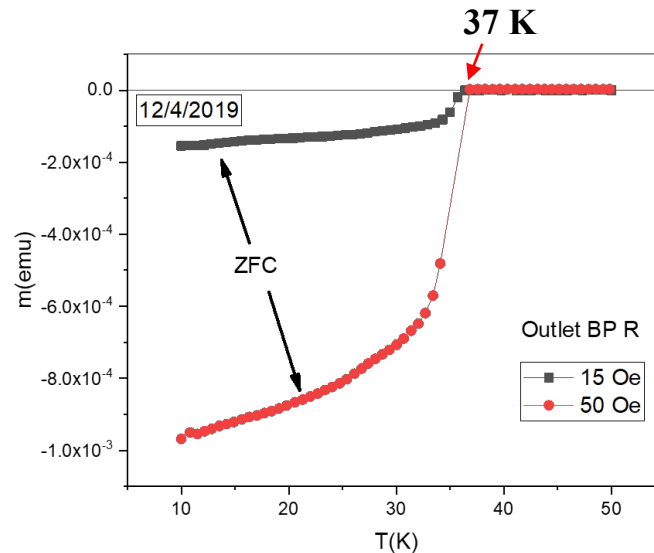
# Recent 2 tests to produce $\text{MgB}_2$ film by reacting B film with Mg vapor

- TA-53 Run 16 on 27 November 2019
  - Hiroshi Sakai and Takafumi Okada from KEK joined LANL workers (Tsuyoshi Tajima and Paolo Pizzol)



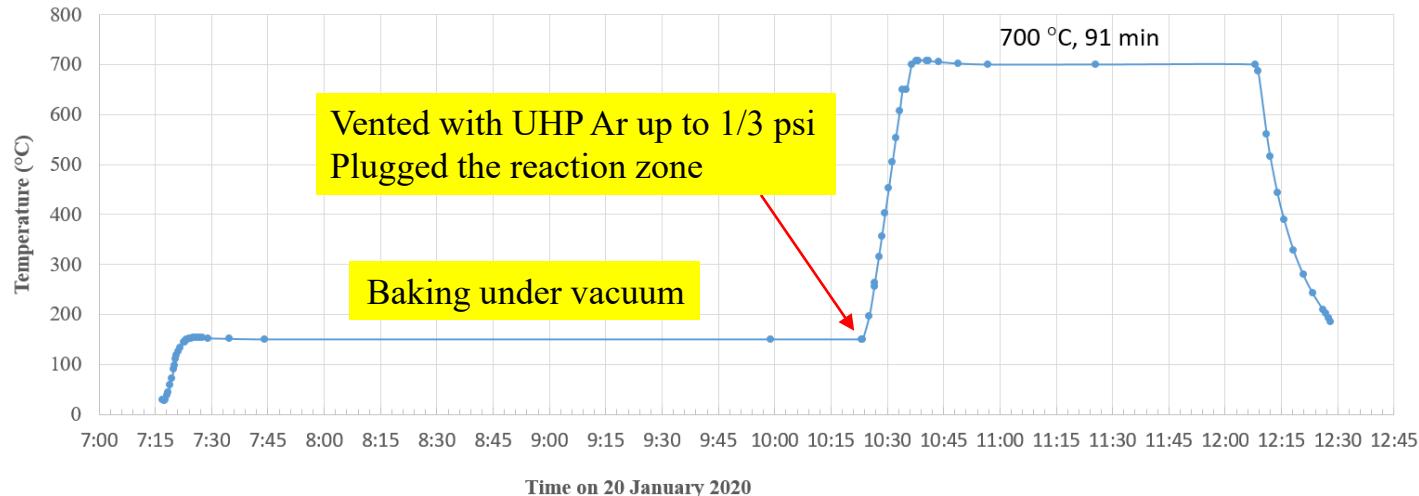
# Magnetometer measurement to check superconductivity

- This was carried out by Ivan Nekrashevich and Leonardo Civale at TA-3 in Leonardo's lab.



# Recent 2 tests to produce $\text{MgB}_2$ film by reacting B film with Mg vapor (cont.)

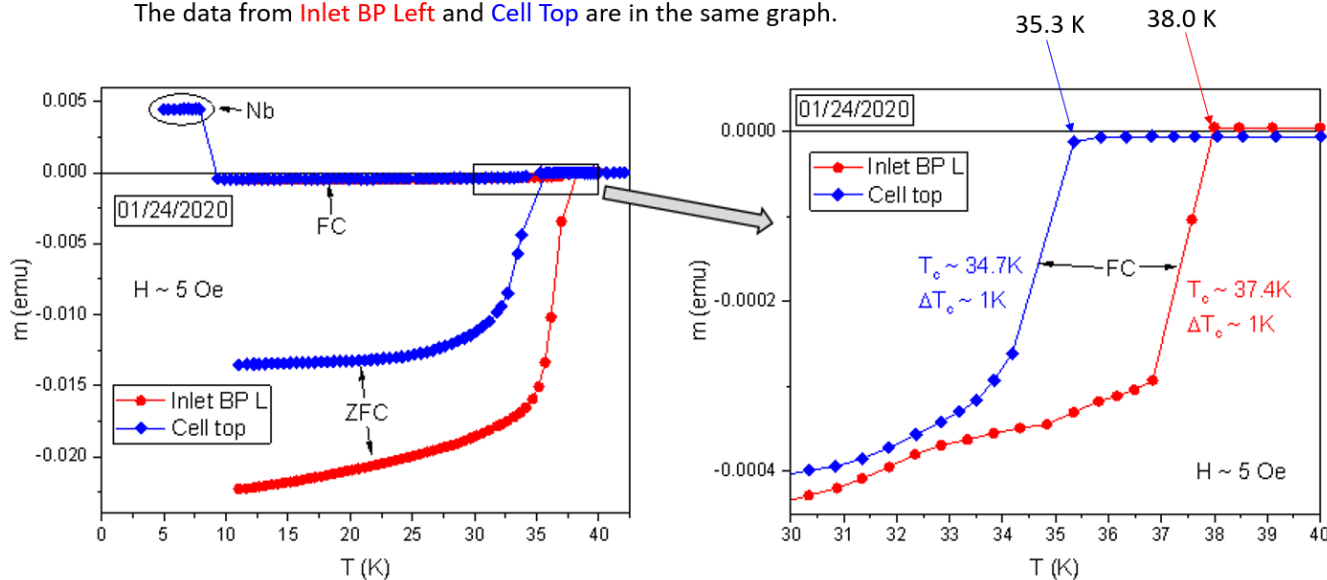
- TA-53 Run 17 on 20 January 2020
  - Tsuyoshi Tajima did it on his own.



# Magnetometer measurement to check superconductivity

- This was carried out by Ivan Nekrashevich and Leonardo Civale at TA-3 in Leonardo's lab.

The data from **Inlet BP Left** and **Cell Top** are in the same graph.



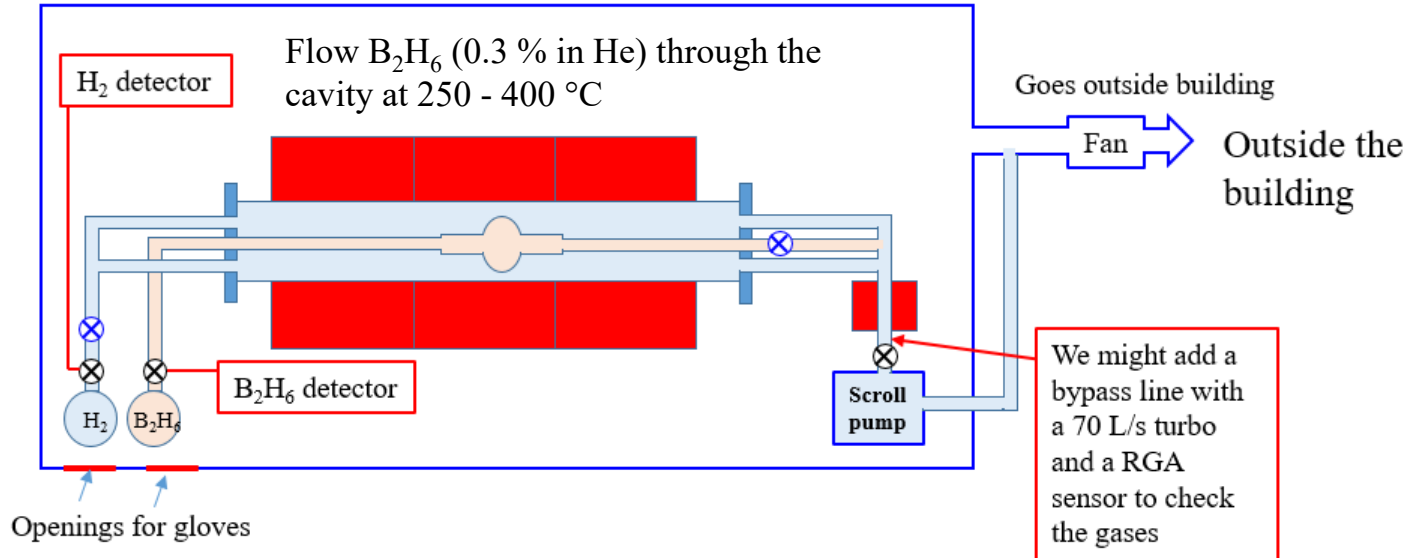
# Summary of recent tests and next steps for parameter optimization

- We were able to reproduce the 750 °C result obtained in 2015.
- The test result at 700 °C was as good as that at 750 °C. (No test at 700 °C in 2015)
- Cell samples showed 3-4 K lower  $T_c$  . Need to identify the reason.
- Will test at 650 °C for 1.5 hours to check if we can reproduce the result in 2015 ( $T_c \sim 32$  K at outlet BP top)
  - If  $T_c$  is  $>35$  K, try 600 °C test.
  - If  $T_c$  is  $<35$  K, try 650 °C for 3 hours to see if  $T_c$  goes up with long reaction time.
- Will test longer cooling time at the lowest reaction temperature that gives  $T_c > 35$  K.
- Will start sample characterizations using AES/XPS from around April or May.

# Design of new coating system (1<sup>st</sup> stage)

- Heater
- Open/close valve (interlocked with gas detectors)
- Pressure control valve including pressure (and flow) sensors

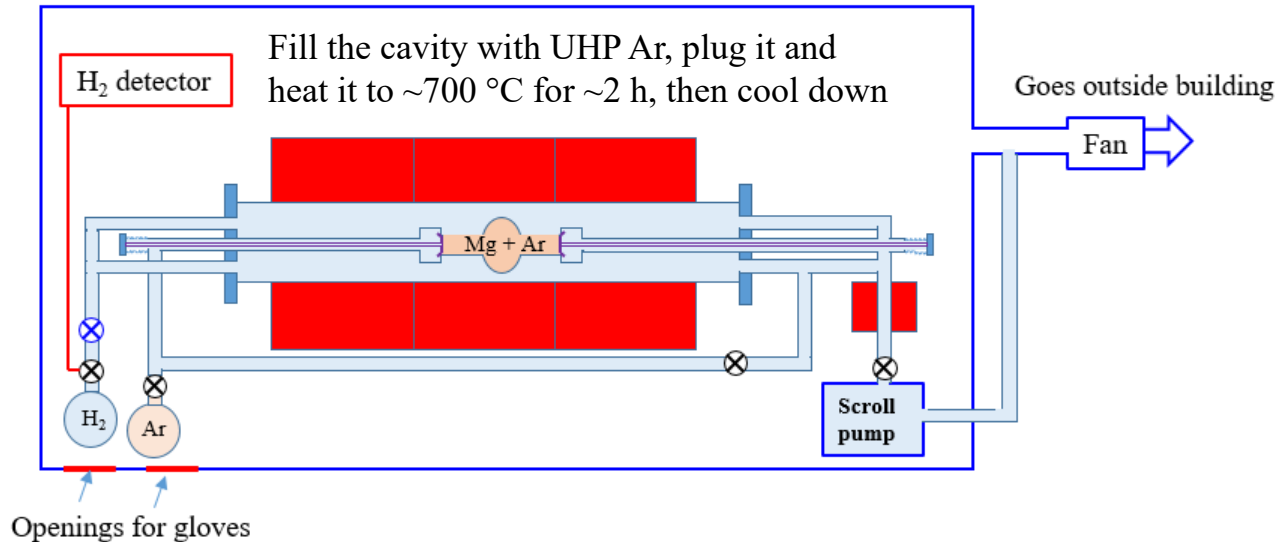
All heaters and valves are remotely controlled through Ethernet



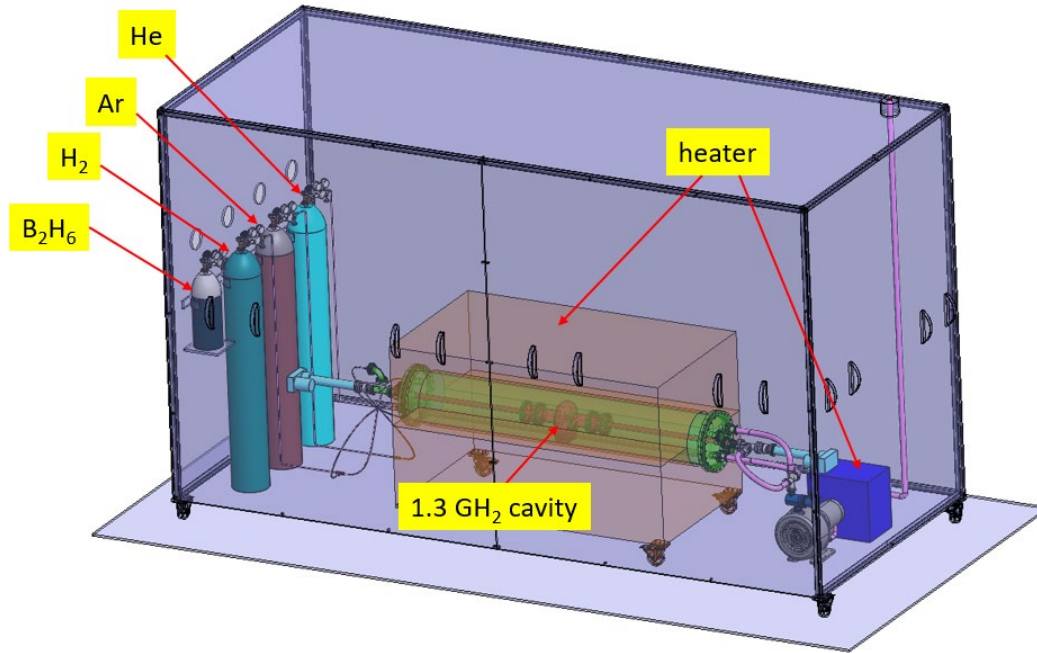
# Design of new coating system (2nd stage)

- Heater
- ⊗ Open/close valve (interlocked with gas detectors)
- ⊗ Pressure control valve including pressure (and flow) sensors

All heaters and valves are remotely controlled through Ethernet



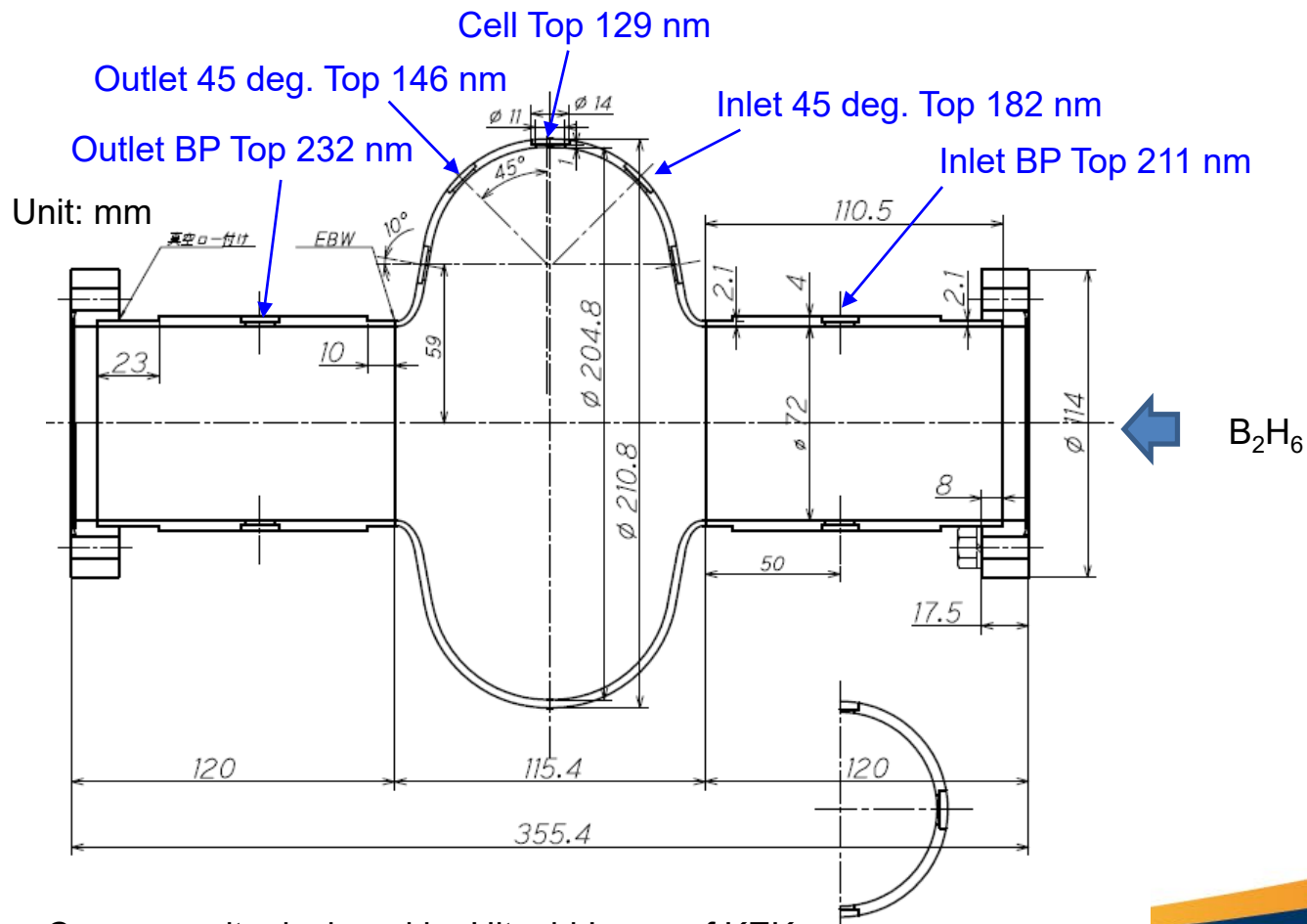
# A 3D model has been constructed



**The following slides show some new results on the thickness measurements of boron samples obtained in 2013 on 06 February 2020**

# Recent result of thickness measurements of B films obtained in a test at TA-03-0040

- Used a spectroscopic ellipsometer alpha SE™
  - J.A. Woollam Co., Inc.
  - <https://www.jawoollam.com/products/alpha-se-ellipsometer>
  - Paolo Pizzol operated the ellipsometer.
  - The samples were from TA-35-213 Run 10 on 13-SEP-2013 (flowing B<sub>2</sub>H<sub>6</sub> gas)
    - The zone 1 was at 300 C, but zones 2 and 3 were at 400 C. This probably reduced the thickness of B on the input BP.



Copper cavity designed by Hitoshi Inoue of KEK

**Thanks for your attention!**

**I would like to thank Sakai-san, Okada-san, Kako-san and others at KEK for their help on this project!!  
I hope we will be able to continue this project until  
we can produce  $\text{MgB}_2$  cavities and test them at  
KEK.**

# Acknowledgements

- LANL
  - Mike Borden, Jim O'Hara and other AOT-MDE group members especially vacuum team members for their support and encouragement
  - Alan Shapiro (retired) and Mike Madrid (retired) for all their work at the SRF Lab.
  - Roland Schulze for AES/XPS analyses
  - Marilyn Hawley for AFM analyses
  - Nestor Haberkorn for magnetization measurements (currently with CNEA-Centro Atómico Bariloche, Argentina)
  - Yingying Zhang and Quanxi Jia for Polymer Assisted Deposition (PAD) studies on NbN and MoN. Dr. Zhang is currently with Tsinghua University, Beijing, China.
  - Leonardo Civale for leading the magnetization measurements and many useful discussions
  - Dave Devlin for setting up the MgB<sub>2</sub> costing system and other coating tests as well as Igor Usov for the coordinations at TA-35-213.
  - Alberto Canabal (now with TriQuint Semiconductor) and Grigory Ereameev (now with FNAL) for testing samples at SLAC and cavities at LANL
  - Alp Findikoglu for measuring  $R_s$  of MgB<sub>2</sub> samples using parallel plate technique.

# Acknowledgements (cont.)

- ANL
  - Mike Pellin and Thomas Proslier for ALD coating of alumina and other studies on dielectric materials. Dr. Proslier is with CEA Saclay now.
- SLAC
  - Sami Tantawi, Jiquan Quo (now at JLAB), Valery Dolgashev, Dave Martin and Charlie Yoneda for preparation and testing samples
- Jlab
  - Binping Xiao for measuring RF surface impedance of  $\text{MgB}_2$  samples using their 7.5 GHz SIC system. Also, Anne-Marie Valente-Feliciano for preparing ECR Nb films.
- Cornell University
  - Alexander Romanenko for conducting  $\text{TE}_{01}$  mode cavity measurements to evaluate  $R_s$  vs.  $H$  for  $\text{MgB}_2$  samples. Dr. Romanenko is currently with FNAL.
  - Hasan Padamsee for useful discussions and encouragement.
- Temple University
  - Xiaoxing Xi and his group members for preparing  $\text{MgB}_2$  samples with HPCVD.

# Acknowledgements (cont.)

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  - Akira Yamamoto, Kenji Ueno, Masashi Yamanaka and Seiya Yamaguchi for support while at Tajima was at KEK on leave from LANL. Hitoshi Inoue for hydroforming and fabricating copper cavities.
  - Shigeki Kato for coordination with a company in Japan for mechanical and chemical polishing of copper cavity
- NIMS, Tsukuba, Japan
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  - Yue Zhao for coating  $\text{MgB}_2$  using PLD technique
- Superconductor Technologies, Inc. (STI)
  - Brian Moeckly and Chris Yung for coating  $\text{MgB}_2$  using reactive co-evaporation technique. (Dr. Moeckly is currently not with STI.)
- Institute for Super Materials, ULVAC, Japan
  - Tomohiro Nagata for SIMS analysis for CED Nb films and useful discussions (Dr. Nagata is currently with KEK on leave from ULVAC)
- Alameda Applied Sciences Corporation, San Leandro, CA
  - Mahadevan Krishnan and Colt James for coating copper cavities with CED technique
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  - DTRA 2008-2010
  - DOE/HP 2018 – present (US-Japan Cooperation Project)